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THE SOLAR CONSTANT.

By FRANK W. VERY, dated September 9, 1901.

At the International Congress of Meteorology held at Paris in September, 1900, M. Violle, the Chairman of the Committee on Solar Radiation, expressed the hope that from the special discussion of this topic, now for the first time recognized as of sufficient importance to demand a place in the deliberations of a meteorological congress, a fresh impulse may be given to this study.

It begins to be recognized that the solar constant may, after all, be a variable with a considerable range, and if so, it is of great importance for meteorology, whether studied rationally for the sake of elucidating the causes of the changes of the weather, or as a practical art of weather forecasting, that a knowledge of the changes in this fundamental datum be obtained from day to day. The difficulties which supervene between the recognition of the importance of this knowledge and its attainment are enormous. M. Angot, at the close of the conference just named, expressed the fear that it may never, perhaps, be possible to arrive at an exact determination of this constant, and considered that at the present time effort must be directed toward perfecting actinometers and multiplying measures of the quantity of radiation which reaches the soil of the earth.

Against this rather disheartening conclusion may be placed the experience of Professor Angström, who, as the result of a comparison of his compensating and differential pyrheliometers, says: "The very satisfactory agreement in the values obtained from the two instruments, which are so different in principle and in their manipulation, speaks, as it seems to me, in favor of their accuracy." The problem of the perfecting of the actinometer, as an instrument capable of giving absolute values, seems to be at least approaching solution. It is rather by the devising of new methods of observation, and by new ways of interpreting and supplementing the results of measurements that further progress is to be made.

Crova's registering actinometer, checked by the indications of an absolute instrument, is capable of multiplying observations to any required extent, and Langley's bolographs give us a promising mode of interpreting results—in fact it is not too much to say that when these invaluable spectral records shall have been furnished under a greater variety of local conditions, carefully studied by the aid of meteorographs at high and low altitudes, and with simultaneous actinographs, checked by measures with a rapid absolute actinometer on Angström's or some equally efficacious plan, we shall have made a long step in the direction of an unimpeachable determination of the true intensity of solar radiation, and may possibly be able to decide the question of its variation at first hand.

The simultaneous occurrence of exceptionally hot weather over the North American and European continents in the summer of 1901, has provoked the conjecture that the sun itself is responsible for such wide-spread abnormal conditions; yet even if this were the case, it is certain that actinometers, read at the earth's surface in the heated zones, would not demonstrate such a solar hot wave, without a simultaneous thorough analysis of the condition of the upper air and the application of appropriate corrections. In fact, the first effect of an unusual increase of solar radiation must be to greatly magnify evaporation of moisture, both from the surface of the earth and from cloud layers, thus supplying the upper air with its most efficient absorbent of radiation. After this abundant replenishing with moisture, the incoming rays are employed to an unusual degree in heating the upper air, and increasing the altitude of the high-level isotherms. Surface temperatures rise because of this general lifting of the altitudinal isotherms, rather than by any immediate action of the direct solar rays which possibly may even be lessened by the increased depth of the layer of especially absorbent material. The true radiation may easily be underrated while such conditions prevail. The change of conditions of the upper air affects the interpretation and correction of the observation for atmospheric absorption, perhaps, to a greater degree than it does the direct reading of the actinometer.

Allusion has been made to similar wide-spread meteorological conditions. It may be urged that world-wide changes of temperature or rainfall are connected with variations in the general movement of the atmosphere dependent upon a shifting of what M. Teisserenc de Bort has named the "centers of action" from which lesser movements are controlled, and that simultaneous and concordant temperature-changes over wide areas should be attributed to this cause in the absence of direct evidence of solar change; but as it is possible that the shifting of the centers of action may itself be due to some change in the general state of the air, inaugurated by solar fluctuations, no definite answer can be given to such questions until they can be treated as parts of a whole.[1]

A consideration of the mutual connection of related constants and physical properties has led me to a mode of testing several hypotheses, which will be described further on. In some such way it may be possible to meet the difficulties which seemed so insuperable to M. Angot.

Although we may have the choice of several instruments and methods which are nearly equally good, there are others which ought to be rejected, and especially those whose theory is too complex for practical use. Among the latter may be mentioned the steam calorimeter of Mr. J. Y. Buchanan, with which in May, 1882, under the rays of a nearly zenithal sun, in the phenomenally dry climate of Egypt, with a dew-point little above the freezing point and an atmospheric transparency which is sufficiently shown by the measured diurnal range of temperature of 44.5° F., the low value of 0.89 small calories per square centimeter per minute was obtained for the effect of solar radiation, to which the inventor, apparently for no well-defined reason, proposes to "add 11 per cent for deficiencies from all sources." In this apparatus the upper part of the condenser was not only exposed freely to air currents, but was in direct metallic connection with extensive surfaces of metal forming the condensing mirror. The loss of heat by convection from all these exposed and conducting surfaces must have been great. It was found, in fact, that wind greatly diminished the measured heat.

The elaborate experiments on Mouchot's solar steam calorimeter, as modified by Pifre, conducted at Montpellier in 1881 by a commission headed by M. Crova, indicated that this device, which is probably quite as effective as Mr. Buchanan's, utilized but little over 50 per cent of the sun's rays. The solar motor recently completed by Mr. A. G. Eneas of Boston, appears to be a notable advance upon its predecessors, but the theory of these instruments is as complex as that of the steam engine, and does not lend itself readily to determinations demanding minute accuracy.

The Arago-Davy conjugate black and bright bulb thermometers, whose mathematical theory has been worked out by Ferrel (see Professional Papers of the Signal Service, No. 13), but with very scant appreciation of the actual complexity of the absorptive process and its variation with the different kinds of radiation present, confounds effects which need to be kept separate, and is another example of that excessive complication which is to be avoided in a reliable working instrument. In 1883 Prof. Winslow Upton made a determination of the solar constant at Caroline Island by the conjugate thermometers in accordance with Ferrel's prescript,[2] but for the reasons given the value obtained can not be accepted.

The student who desires to follow the steady progress that has been made in this department should consult a valuable little work by M. Radau, Actinometrie, published by Gauthier-Villars at Paris in 1877, which gives a concise and clear account of what had been accomplished at that date. It is there recognized, on the strength of the experiments of Jamin and Masson on the transmission of radiation by colored glasses, that there is an exact proportionality between the luminous and thermal effects of simple or homogeneous rays. But a like proportionality does not hold for rays of different wave-lengths, and while luminous effects may be regarded as dependent on a certain photo-chemical action upon the retina, not all photo-chemical processes are equally definite and measurable. As M. Radau says (loc. cit., page 11): "The red rays and the yellow rays in certain cases continue the work commenced by the violet rays, and in others undo what the last have accomplished. Thus chloride of silver, slightly impressed by the violet rays, is then blackened under the action of all of the visible rays; and guaiacum, turned blue by the violet rays, is bleached by the more luminous rays. It follows that the chemical action of light is, in general, very complex, and that it can be used for measuring the energy of solar rays only with much circumspection."

M. J. Vallot and Mme. Gabrielle Vallot arrive at a similar conclusion in their "Experiments in chemical actinometry executed simultaneously at different altitudes and at diverse temperatures" in the Alps in 1897 (Annales de l'Observatoire Météorologique du Mont Blanc, vol. 3, page 81, 1898). The reaction consists in the decomposition of a solution containing 3 grams of oxalic acid per liter of water with evolution of carbon dioxid, when exposed to the sun's rays in a shallow dish. M. Duclaux, to whom the method is due, had found that heat alone produces only a negligible decomposition; that the reaction does not begin immediately upon exposure, and undergoes continued acceleration as insolation is prolonged; also that the decomposition is greater in August and September than in October on the clearest days. M. and Mme. Vallot, on repeating and extending these experiments, find that the evolution of CO_2 increases from three to five times when the mean temperature of the liquid is raised from 20.5° C. to 32.4° C. Hence, while heat alone can not start the action, it can greatly accelerate the decomposition by light, and in this respect the reaction resembles that which takes place in growing plants under the action of sunlight, where the organic development depends, other things being equal, upon a quantity proportional to temperature and illumination combined. No direct experiments were made to determine the region of the spectrum where the actinic power to decompose oxalic acid resides, save the observation of a strong obstruction by glass; but an increase of over 100 per cent was found for an ascent of 830 meters, from 1,095 meters to 1,925 meters, and an increase of over 400 per cent in the first part of August over the result for the last part of September, with equal duration of exposure, which may be partly induced by a higher temperature of the liquid in August and under the more powerful radiation of the higher altitude.

It is obvious that chemical actinometers are entirely without value for the determination of the solar constant, but they may have a use in estimating an integrated radiant and thermal function on which the growth of plants largely depends.

As M. Radau says (loc. cit., p. 9), all of the rays of the solar spectrum, whether belonging to the visible, the infrared, or the ultra-violet regions, "are more or less warm [or

[1] See my paper on "The variation of solar radiation," Astrophysical Jour., vol. 7, p. 255, 1898.

[2] See Report of the Eclipse Expedition to Caroline Island, May, 1883, Memoirs of the National Academy of Science, Vol. II, p. 81.

rather calorific] and produce more or less pronounced chemical effects; but practically it is always a limited region of the spectrum which produces the observed effect."

In photography it is very evident that the rays absorbed by the film, and usefully employed in producing chemical change, are confined to narrow spectral regions. It is less obvious that a substance like lampblack, which, in a comparatively thin layer, absorbs almost totally the rays of the ultra-violet and visible spectra, and also a large part of the infra-red, has its limitations as an absorbent in like manner; but the discovery of extreme infra-red rays having a wave-length (at the rock-salt maximum) of at least 50 microns, and requiring special means for its absorption and measurement, has emphasized Melloni's observation that, for radiation from sources of low temperature and from such bodies as rock-salt, lampblack behaves as a partially transparent body. While the transformation of radiation into heat by black bodies and the registration of this heat by some thermometric device is more complete than any other action depending on radiant absorption, it is necessary, therefore, to remember that there is no universal or absolute absorbent. To guard against error from this source and enable radiation of a wider range of wave-length to record itself more completely, Paschen has devised an instrument for measuring radiation in which the thermometric surface (of thermopile or bolometer), being prepared with successive coats of platinum black and lampblack to increase its absorption, is placed at the center of a hemispherical mirror which returns the rays, entering by a central aperture and diffusively reflected from the partially absorbent surface, repeatedly to that surface, whereby an increasing percentage of the residual radiation is transformed into heat at each return to the blackened surface.[3] In this way a very close approach to the ideal absolutely black body is obtained, and a notable increase in the calorific power of extremely long ether-waves is recorded. For the direct actinometric measurement of solar radiation the method has little application, since the greater part of the solar radiant energy resides within the region for which absorption by lampblack is almost complete; but for the indirect estimation of the solar radiant energy outside the atmosphere, it is very desirable that spectral energy-curves shall be obtained in their true forms, and this, for the first time, can now be accomplished by the aid of Paschen's repeating bolometer.

M. Radau has the merit of having perceived the usefulness of spectroscopic measures in the determination of the solar constant. "The formula, $I = A p^{\epsilon}$, applies to a bundle of homogeneous rays. The intensity of the total radiation of the sun, transmitted by the atmosphere, ought to be expressed by a series of terms each relating to a particular bundle [or kind of radiation, whence]

$$I = A p^{\epsilon} + A_1 p_1^{\epsilon} + \ldots,$$

the primitive intensity being the sum, $A + A_1 + \ldots$ When the thickness ϵ does not vary much, the observations are ordinarily represented with quite sufficient precision by the formula with a single term, $I = A p^{\epsilon}$, by taking a mean value for p; but when the sun approaches the horizon a single term no longer suffices for the calculation of the observations. The mean value of p increases greatly when ϵ becomes very large, because the terms of the complete formula, where the coefficients p are small, disappear little by little, so that there remain only terms whose coefficients are near unity. Hence, by contenting ourselves with a single term, we find for p values so much the greater as the measures have been made nearer the horizon. This is, in fact, what the observations of Forbes, of Quetelet, and of Desains have confirmed. The coefficient [of transmission] p increases, and a [which in Radau's equations signifies the logarithmic coefficient of absorption] diminishes in proportion to the growth of ϵ; that is to say, the solar radiation becomes *more transmissible* as it traverses larger masses of air, because it is deprived little by little of the more absorbable rays" (loc cit., p. 24).

But while the real nature of the problem was pointed out in these words, no one attempted to apply them until Langley made his memorable expedition to Mount Whitney (see Professional Papers of the Signal Service, No. 15) and began the detailed investigation of the infra-red spectrum, obtaining, in his Researches on Solar Heat, coefficients of atmospheric transmission for a small number of points in the spectrum within the range of a glass prism, and applying this knowledge in a redetermination of the solar constant, whose reliability remains unapproached by any other measurement, for, with the exception of Angström, no one has attempted to follow up the advantage gained by this new mode of attack.

By these earlier spectrobolometric researches, Langley established the distinction between two different kinds of selective depletion which the solar rays suffer in traversing the earth's atmosphere. One kind is greatest for the rays of shorter wave-length and diminishes by perfectly regular gradations as we pass toward the longer waves of the infra-red. Its cause may be referred to selective reflection or diffraction of the shorter ether-waves by particles of excessive minuteness. The other kind of absorption produces irregular gaps or depressions in the spectral energy-curve, which begin at the red end of the visible spectrum and grow in magnitude and frequency as the wave-length increases. Researches by Abney and Festing, and by other investigators, have traced the majority of these depressions to the action of aqueous vapor.

The use of rock-salt prisms has since greatly extended this new infra-red region, showing a further increase in the number and intensity of these aqueous absorption bands, until they coalesce in a great region of almost total absorption between $5\,\mu$ and $8\,\mu$, first depicted in the memoir on The Solar and the Lunar Spectrum, communicated by Langley to the National Academy of Science in 1886, and printed in its Memoirs, Volume IV. Beyond this region of intense absorption the air again becomes transparent, but as these extreme rays have little importance for absolute measurements of solar energy, it is sufficient to describe the two principal sorts of telluric absorption which affect the solar spectrum as increasing in opposite directions, leaving a middle region of the spectrum comparatively unaffected.

In the recently published Annals of the Astrophysical Observatory of the Smithsonian Institution (vol. 1, 1900, by S. P. Langley, Director, aided by C. G. Abbot), Langley, in describing his earlier paper of 1883 on "The selective absorption of solar energy," says: "These measurements confirmed the earlier conclusion that the maximum ordinate of the normal energy-curve was in the orange, and showed that the absorption of the earth's atmosphere [by selective scattering] increased rapidly with *decreasing* wave-lengths, then a novel statement, for, strange as it may now appear, it was even at this late time very generally supposed to increase most in the lower red, though the simple aspect of a sunset might have taught the contrary" (Annals, p. 11). In order to do fuller justice to earlier investigations, I would remark that in 1869 Tyndall, completing the imperfect conjectures of his predecessors, had found the cause of the blue color and the polarization of the light of the sky in selective reflection from fine particles. His explanation had been generally accepted. Clausius had shown that for a solar altitude of 10° the light diffused by the sky was more than double that coming directly from the sun. Lord Rayleigh had given in 1871 a mathematical expression for the intensity of homo-

[3] F. Paschen. Sitzungsberichte der Akad. der Wissenschaften zu Berlin, 1899, part 1, p. 405; Astrophysical Jour., vol. 10, p. 40, 1899.

geneous rays of wave-length λ, whose initial magnitude I_0, after transmission through a turbid medium of thickness ε, becomes:

$$I = I_0 e^{-k \lambda^{-4} \varepsilon}.$$

This formula, with suitable values of k, is capable of representing the observed changes, due to generally selective reflection, which result according to subsequent measures. M. Radau, in 1877, says (Actinometrie, p. 101): "The coefficient of transparency is more feeble for the rays belonging to the violet region of the spectrum and for the dark chemical rays, as it is also very feeble for the dark [infra-red radiant] heat," thus recognizing a middle region of the solar spectrum more transmissible than the ends, which accords with the facts.

It is true that statements can be found in which the telluric absorption is described as greatest at the red end of the visible spectrum, meaning, of course, the atmospheric band absorption which becomes pronounced in the spectrum of the sky, after sundown; but such statements are but analogous to some passages in these Annals which require mutual interpretation. For example, in the summary, p. IV, we read: "The infra-red region is shown to be the seat of the principal telluric absorption of the solar energy," and in the summary in Chapter VIII, p. 216, "the infra-red is the seat of great terrestrial atmospheric absorption," while on page 11 we find that "the loss in passing through the atmosphere was chiefly confined to the shorter wave-lengths," and on page 14, we learn that "in spite of these absorption bands, the principal portion of infra-red solar energy is transmitted more freely than the visible." (See also page 208.) These apparently conflicting statements may easily puzzle a novice. The discrepancy is partly due to an imperfect characterization of the two leading kinds of absorption. To complete the idea something must be supplied from the context. Besides this, there is a different use of the term *absorption*, which represents in the first place a percentage ratio whose distribution in the spectrum may be considered apart from the actual intensity of the radiation, but which may also represent the amount of energy which has disappeared. The "principal portion" of solar infra-red energy lies outside the region of the *principal infra-red absorption* in the first sense of the word. Hence, while the solar rays suffer their greatest percentage of telluric absorption through extensive regions in the extreme infra-red, the larger portion of solar infra-red rays lies outside the bands, and is rather freely transmitted.

On page 205, and again on page 214 of the Annals, doubt is thrown on a "suspicion" that the bands $\rho\ \sigma\ \tau$, and Φ are telluric, as "has been affirmed of them by Abney" (Proceedings of the Royal Society of London, vol. 35, p. 80, 1883); and on page 216 of the Annals, in speaking of the absorption exercised by layers of 6 millimeters, and of 13 millimeters of water, it is said: "It appears certain that the band Φ is not due to water or water vapor. The absorption of water begins just at the long-wave side of Φ, is moderate up to Ψ, very great for a strip about 2′ wide on the long-wave side of Ψ, moderate between Ψ and Ω, but still greater than between Φ and Ψ, very great for a little distance below Ω, and very considerable from here on." The attentive reader will, of course, recall the complete demonstration by Abney and Festing (Proceedings Royal Society of London, vol. 35, p. 328, 1883), that not only the bands in question, but also four others of shorter wave-length. are of aqueous origin. Much greater depths of water, up to 24 inches, were used by these experimenters. The bands $\rho\ \sigma\ \tau$ and Φ are perceptible in the spectrum after absorption by only $\frac{1}{8}$ inch of water, but do not become pronounced until a much greater depth is passed.

In my memoir on Atmospheric Radiation (Bulletin G, United States Weather Bureau, p. 104, 1900), I have computed the percentage transmissions from the curves given by Abney and Festing, obtaining for a layer of $1\frac{3}{4}$ inches of water:

	Transmission. *Per cent.*
At the rain band in the yellow	91
Maximum in orange-yellow	98
Orange band due to water	88
Maximum in red	96
Red band (near A) due to water	88
Maximum near Brewster's Y	90
Band between X and Y, due to water	85
Maximum (Herschel's α)	87
Band (Abney's $\rho\ \sigma\ \tau$) due to water	19
Maximum (Herschel's β)	33
Band (Abney's Φ) due to water	2
Maximum (Herschel's γ)	8

All beyond the maximum between Φ and Ψ is totally absorbed by this depth of water.

Paschen, in 1894 (Wied Ann., vol. 51, p. 22), noted that the absorption bands of liquid water, while beginning at the same points as those due to aqueous vapor, are broader on the side of greater wave-length; and Abney and Festing have shown the existence of two kinds of absorption bands in the solar infra-red spectrum (linear and diffuse), which I have suggested, may be attributed to diverse molecular states of water vapor, connected with variations in relative humidity. (See Atmospheric Radiation, pp. 90–105.) In view of these facts it becomes necessary to include both tension of aqueous vapor and relative humidity in the expressions that represent the absorptive influence of the aqueous component of atmospheric absorption, as well as the complex λ-function on which the local band variations depend.

If, with Lord Rayleigh, we attribute the blue color of a sky, entirely free from haze, to the diffraction of the gaseous molecules, it may be necessary also to divide the expression for selective scattering into two parts: one to include molecular action, in which ε varies with the path of the rays (computed by Laplace's formula) and with the barometric pressure; the other due to atmospheric dust of the finest sort, which ordinarily only ascends to a height of 4 or 5 kilometers, which is independent of the barometric pressure, and for which ε' had best be computed by Lambert's formula:

$$\varepsilon' = \sqrt{1 + 2r + r^2 \cos^2 \zeta} - r \cos \zeta,$$

in which r has some such value as 5 kilometers, depending on the height of the upper limit of the dust layer.

ζ	ϵ' (dust.)	ϵ (air.)	ζ	ϵ' (dust.)	ϵ (air.)
°			°		
10	1.013	1.016	60	1.653	1.995
20	1.053	1.065	70	2.021	2.902
30	1.124	1.156	80	2.560	5.571
40	1.236	1.306	85	2 909	10.216
50	1.405	1.555	90	3.317	35.503

To this must be added the indiscriminate or nonselective scattering of rays without much regard to wave-length, which is chiefly accomplished by the coarser ice or water particles of the clouds, for which no law can be formulated, and which must be eliminated by confining our observations to the clearest days.

As to the absorption of solar rays by carbon dioxid, Prof. Knut Angström, in his recent paper "On the importance of water vapor and carbon dioxid in the absorption by the earth's atmosphere" (Ann. der Phys. (4), vol. 3, p. 720, 1900), concludes that the air contains enough of this gas to produce complete absorption within the limits of its bands. Consequently this absorption is best expressed by a constant, graphically estimated from a restored spectral energy-curve.

In the words of Violle: "We must therefore henceforward entirely renounce the 'barbarous' expression, to use Dr. Pernter's phrase, of a single coefficient of transparency relative to the action of our atmosphere on the total radiation of the sun. But after the results of the researches carried out or suggested by Langley, how complicated does this absorption appear!"

We may consequently pass by the numerous formulæ which attempt to find the solar constant with only one, or at most, two terms. Such formulæ may represent actinometric values obtained within a limited range of conditions quite perfectly, but can not be extended much beyond that range. Pouillet, from the close concordance of his results obtained by using a simple formula and an instrument having large constant errors, felicitated himself on having arrived at such an exact value of the solar constant that he could be permitted to draw improbable conclusions in regard to the temperature of space; and in the Annales de l'Observatoire Météorologique de Mont Blanc (vol. 2, 1896), we find M. J. Vallot resting in the same fatuous security, and adopting for the solar constant 1.7 small calories per square centimeter per minute from the mean of four series having an extreme variation of 2 per cent, with the remark: "This concordance of results authorizes us to believe that those which we give depart little from the truth" (page 147). M. Radau (Actinometrie, p. 29) has shown that as long as we are contented with an apparent concordance of a few per cent, the mean results of our actinometric observations through a limited range can be represented by a great variety of empirical formulæ; and he notes that "the only useful formulæ are those whose constants admit of a physical interpretation." Langley (Researches on Solar Heat, p. 45) remarks that "in solar actinometry, the mean of all our observations is never really the most probable, and the true value is always, and necessarily, higher than this mean;" and in Chapter X of the same work he proves that "the error increases with the difference between the coefficients" of transmission for different rays, when these are not discriminated, and that apparently concordant results, obtained by the application of such simple formulæ as that of Pouillet, are grossly erroneous.

Notwithstanding these demonstrations, the devising of simple empirical formulæ continues with, perhaps, little use, save as ingenious mathematical exercises. The reader who cares to follow these developments will find a succinct account of many such formulæ in the Report on Radiation, by M. Jules Violle, in the Report of the Proceedings of the meeting of the International Meteorological Committee at St. Petersburg, September, 1899, under the heading "Formulæ" (p. 60).

As an example of the fallacies which lurk in such formulæ, we may notice one proposed by Angström in 1899, but which was subsequently completely demolished by his own investigations. Dividing the solar radiation into two parts: A_1 composed of rays affected by the absorption through aqueous vapor, oxygen, and nitrogen; A_2 consisting of rays absorbed by carbon dioxid; p_1 and p_2 being the corresponding coefficients of transmission, the observed intensity of solar radiation is represented by the formula:

$$Q = A_1 p_1^{\epsilon} + A_2 p_2^{\epsilon}.$$

Assuming that the rays capable of being absorbed by CO_2 have completely disappeared for values of ϵ greater than 3 atmospheres, the values:

$$A_1 = 1.56, p_1 = 0.786,$$

are first obtained by the one-term formula applied to low-sun observations. Then, subtracting the values computed by the formula, $Q_1 = 1.56 \times (0.786)^{\epsilon}$, from the results of observation in six other cases where ϵ varies between 2.26 and 1.26, and adopting a mean coefficient for the rays absorbable by CO_2, viz: $p_2 = 0.134$, derived from his own observations, combined with others by Lecher (but which, as it appears from later measures, contain large errors), Angström obtains from the residuals, $A_2 = 2.45$, whence the solar constant becomes:

$$A_1 + A_2 = 1.56 + 2.45 = 4.01.$$

In regard to this method, I have remarked (Atmospheric Radiation, p. 105) that it "leads to the absurd result that over 60 per cent of the original solar radiation is contained in the spectral region occupied by the bands of carbon dioxid. The limits of these bands have now been ascertained, and it is certain that they do not cover a length of the solar spectrum possessing more than a small fraction of this proportion of total radiant energy," and that it is inadmissible to raise the solar constant to 4 calories *on these grounds*. It is only fair to state that this has since been independently recognized by Professor Angström himself.

M. Vallot, as already stated, observing on Mount Blanc with a Violle actinometer, computes a value of 1 7 for the solar constant, which is less than has been obtained directly for the solar radiation, *after absorption*, by reliable measures at high elevations.

As all of M. Vallot's observations have been made with positive values of θ (the excess of the sun thermometer), it is necessary to add a correction (A) for losses by convection. It would be much better to conduct measures with the Violle actinometer, so that there shall be approximately equal positive and negative values of θ, which, when combined, will obviate the need of this correction.

Another important correction which has not been applied is that for the imperfect conductivity of mercury (B), and a determination of the errors due to imperfect absorption is desirable. In the following table, I have applied corrections (A) and (B) to Vallot's measurements. The corrections for imperfect absorption by the surface of the thermometer bulb (positive) and for radiation reflected by the sky around the sun (negative) are not known. The first is no doubt larger than the second, hence the corrected values will still be a little too small. Following Langley,

$$\text{Correction } (A) = + \frac{H}{760} \times 14.3 \%.$$

$$\text{Correction } (B) = + \cos \tfrac{1}{2} \zeta \times 8.3 \%.$$

Station: Mount Blanc.						Station: Chamonix.					
Time.	ζ	$\frac{H}{760} \times \epsilon$.	I obs.	Cor.	I cor.	Time.	ζ	$\frac{H}{760} \times \epsilon$.	I obs.	Cor.	I cor.
h. m.	° ′	*Atm.*	*Cal.*	*Cal.*	*Cal.*	*h. m.*	° ′	*Atm.*	*Cal.*	*Cal.*	*Cal.*
5 31	81 45	3.890	0.980	+.141	1.121	......	......	......	......	......	......
7 40	59 5	1.105	1 428	+.218	1.646	7 26	62 0	1.912	1.080	+.214	1.294
9 20	42 56	0.768	1.458	+.230	1.688	9 14	43 46	1.224	1.198	+.244	1.442
1 14	31 14	0.655	1.565	+.252	1.817	1 34	33 30	1.064	1.287	+.266	1.553

The precipitable water above the summit is supposed to have been 1.7 millimeters; that above the lower station, 25 millimeters.

These results may be compared with the following, obtained by Langley's expedition to Mount Whitney, also made with Violle's actinometer (corrections applied):

Station: Mountain Camp.			Station: Lone Pine.		
ζ	$\frac{H}{760} \times \epsilon$.	I.	ζ	$\frac{H}{760} \times \epsilon$.	I.
° ′	*Atm.*	*Cal.*	° ′	*Atm.*	*Cal.*
66 56	1.675 (a.m.)	1.554	70 33	2.600 (a.m.)	1.441
62 9	1.411 (a.m.)	1.752	66 56	2.216 (p.m.)	1.355
60 58	1.352 (p.m.)	1.617	64 33	2.024 (a.m.)	1.571
26 38	0.738	1.882	60 58	1.797 (p.m.)	1.423
26 7	0.734	1.909	26 38	0.976	1.696
(Peak) =	[0.655]	[1.954]	26 7	0.972	1.718

The larger values of solar radiation on Mount Whitney are no doubt due to the extreme dryness of the air. The altitude of the peak of Mount Whitney (4,460 meters) is somewhat less than that of Mount Blanc (4,810 meters), and Lone Pine Camp (1,184 meters) is a little higher than Chamonix (1,040 meters); but the temperature in the middle of the day in July amid the snows of Mount Blanc was several degrees below freezing point, and the aqueous vapor was nearly saturated, whereas in the final measurement at the peak of Mount Whitney the air temperature was + 16.9° C.; moreover, as an observation with Regnault's hygrometer on another occasion gave a dew-point of −12.5° C., while the mean dew-point by psychrometer (September 1–3) was − 11.6° C., it is quite likely that the air immediately above Mount Whitney was nearly dry, since the observed dew-point would give a relative humidity of only 12 per cent. Even so small an amount of moisture as this, however, is able to exert a large absorption on radiation which has not been depleted of the rays falling within the limits of the aqueous bands, and M. Vallot's assumption that the aqueous absorption is proportional to the amount of aqueous vapor penetrated by the rays, is far from correct. Moreover, any approach to saturation of the aqueous vapor brings out the diffuse absorption bands peculiar to complex aqueous molecules, and adds still more to the losses produced by this ingredient of the atmosphere. It is for these reasons that M. Violle's formula for the solar constant,

$$I = A\,p^{\left[\frac{H+(Z-z)kf}{760}\times\epsilon\right]},$$

fails. In fact, k, by which the force of vapor (f) is to be multiplied, can not be a constant, nor is the aqueous absorption proportional to $Z - z$, the depth of the moisture-holding layer of the atmosphere above the place of observation.

By entirely rejecting his low-sun observation, not because it is too small, and therefore to be suspected of failing from interference of the mists near the horizon, as happens in too many cases with a low sun, but because it is too large and disagrees with preconceptions founded on an empirical formula, M. Vallot is able to compel his remaining data to fit Violle's supposed law. It is quite unnecessary to pay any further attention to the value of A thus deduced; but the original measurements, with the proper corrections, are worth preserving.

Dr. G. B. Rizzo, in his memoir on the solar constant (Accad. Reale d. Sci. di Torino (2), vol. 48, p. 319, 1898), besides giving a series of actinometric measures made by himself and assistants on Rocciamelone, resulting in reduced zenithal values of 1.61 calories at an elevation of 501 meters, 1.98 calories at 1,722 meters, 2.09 calories at 2,834 meters, and 2.13 calories at 3,537 meters, has recomputed the spectrobolometric measures made by Langley at Mount Whitney, using an empirical formula:

$$Q_\lambda = \frac{A_\lambda}{(1+\epsilon)^m},$$

where A_λ is the value of the original homogeneous radiation of wave-length λ, Q_λ is the same after passing air mass ϵ, and m is a constant, best satisfying the high and low-sun observations. The formula is derived from that used by Crova in reducing his actinometric measures, and gives an outside curve with the maximum at 0.5 μ. The principal advantage of this formula is that it allows us to express the observed fact that the coefficient of transmission,

$$p = \left(\frac{1+\epsilon_1}{1+\epsilon_2}\right),$$

increases with low altitude of the sun. It does not eliminate inconsistencies. Thus, some of the values of A_λ, obtained from mountain and valley observations, differ by over 100 per cent. Dr. Rizzo, in fact, only uses the formula to obtain values of $Q_{1\lambda}$ for $\epsilon = 1$, which he then transfers to a barometric formula:

$$Q_1 = A + B\,(760 - H)^{\frac{1}{2}}.$$

No improvement is affected by this method, which gives altogether too little absorption in the ultra-violet, yet there can be no doubt that these valuable measures are capable of yielding improved results, if treated by a rational theory.

The spectral region covered extends from 0.35 μ to 1.2 μ in the grating spectrum, and is chiefly affected in passing through the atmosphere by selective scattering of the rays from fine particles. The infra-red region beyond 1.2 μ is mainly influenced by band absorption, due to aqueous vapor and carbon dioxid. As a first approximation, let us assume that the two regions are, on the whole, equally depleted, each by its own peculiar process of degradation, and that the total energy of either region, as measured at the two stations, may be approximately equalized to the ratio of actinometric measurements.

Lord Rayleigh's later formula for diffraction from the air molecules (Phil. Mag. (5), vol. 47, p. 375, 1899) gives a smaller residual from observation in the visible and ultra-violet spectrum, but one which is less regular than that deduced by his formula of 1871 (Phil. Mag. (4), vol. 41, p. 107):

$$[\mathrm{R}] \qquad I = I_0 \times e^{-k\lambda^{-4}\epsilon},$$

I_0 and I being intensities outside and inside the atmosphere, e the basis of natural logarithms, k a constant depending on the properties of the fine particles, λ the wave-length of the homogeneous rays, and ϵ the air mass. I shall assume that this equation represents the diffraction by air molecules, and that the value of k is 0.01. The air mass (ϵ) is given in atmospheres, the barometric pressure and the length of path (as given by Laplace's formula) are included in it.

The reflection from even the finest atmospheric dust, whose particles much exceed molecular dimensions, is only moderately selective, and the exponent of λ can not greatly surpass unity. I shall adopt Lord Rayleigh's earlier formula, with the subtitution of $\lambda^{-1.5}$ for λ^{-4} to express the depletion of the rays by atmospheric dust:

$$[\mathrm{D}] \qquad I = I_0 \times e^{-k'\lambda^{-1.5}\epsilon'},$$

The value of k' will depend on the amount of dust in the air. A dense haze or smoke, giving a blood-red sun, lets only 2 or 3 per cent of red light pass, although I have found over 50 per cent of infra-red radiation transmitted under these circumstances. Here k' may be taken equal to 2.0. At the Mountain Camp, Mount Whitney, Langley found the atmospheric dust much diminished (Researches on Solar Heat, p. 41). We may take k'=0.125 for this condition, and k'=0.25 for the dust constant at Lone Pine. The dust layer is assumed to ascend to a height (r) of 2 kilometers above the upper station, and 5 kilometers above the lower station, and the value of ϵ', which in this case does not depend upon barometric pressure, is to be computed by Lambert's formula.

The noon values of the spectral energy-curves are taken from the table on page 189 (Researches), in accordance with the footnote on page 137, and the explanation on page 188.

Mount Whitney...	ζ = 29° 21′,	ϵ = 0.753,	ϵ' = 1.09.
Lone Pine........	22° 38′,	0.943,	1.07.

The transmissions through the given masses for air molecules (R) and for dust (D) are given, together with the observed values of I and the computed values of I_0 in the following table:

λ	Mount Whitney.				Lone Pine.			
μ	R	D	I	I_0	R	D	I	I_0
0.35	.6055	.5180	43.1	137.4	.5335	.2747	25.1	171.3
0.375	.6838	.5525	47.3	125.8	.6207	.3111	28.4	147.1
0.40	.7452	.5836	77.2	177.5	.6920	.3474	50.1	208.4
0.45	.8323	.6368	187.8	354.3	.7943	.4122	110.6	337.8
0.50	.8865	.6803	246.9	409.4	.8600	.4692	153.9	381.3
0.60	.9436	.7459	269.3	382.6	.9298	.5623	201.0	384.4
0.70	.9692	.7925	231.6	301.5	.9614	.6333	191.1	313.9
0.80	.9817	.8266	172.0	211.9	.9772	.6882	155.5	231.2
1.00	.9927	.8724	108.2	124.9	.9906	.7652	100.2	132.2
1.20	.9963	.9016	77.8	86.6	.9954	.8158	76.4	94.1

The aberrant ultra-violet values for $\lambda = 0.35\ \mu$ are probably illusory, as the impure spectrum is liable to contain at this point much stray light from the hotter regions near the maximum. Moreover, the necessary corrections for losses in reflection from metallic surfaces of mirrors and grating, form a relatively large part of the observed value in this region, increasing the chance of error. Hence, I have not retained these values in measuring the areas of the curves. The spectral energy-curves show maxima at the following points:

Outside,	$0.532\ \mu$
Mount Whitney,	$0.579\ \mu$
Lone Pine,	$0.632\ \mu$

and the areas of the curves to $1.2\ \mu$, rejecting the observations at $\lambda = 0.35\ \mu$, are:

λ	λ=0.2 to 0.3	λ=0.3 to 0.6	λ=0.6 to 0.9	λ=0.9 to 1.2	Total 0.2 to 1.2μ
Outside the atmosphere	0.4	41.2	40.5	17.9	100.0
Mount Whitney	0.0	23.9	30.6	15.2	69.7
Lone Pine	0.0	15.4	25.9	14.3	55.6

Additional loss by band absorption, chiefly between λ 0.6 and 1.2 (estimated from spectral energy-curves)	7.0
Transmission by curves (Mount Whitney)	62.7
Transmission by curves (Lone Pine)	48.6

By Violle actinometer (corrected), Mount Whitney radiation $= 1.896$
By pyrheliometer (mercury standard), Lone Pine radiation $= 1.533$

$$\text{Solar constant (Mount Whitney)} \frac{1.896}{0.627} = 3.024 \text{ cal.}$$

$$\text{Solar constant (Lone Pine)} \ldots\ldots \frac{1.533}{0.486} = 3.154 \text{ cal.}$$

These results indicate that k', which has been taken twice as great for the lower station as for the upper, should be slightly diminished for the lower station, since the reductions to mean solar distances are + 2.5 per cent for Lone Pine, and + 1.6 per cent for Mount Whitney.

If the assumption of equal total depletion for the regions above and below $1.2\ \mu$ were exact, these ratios would give for the solar constant 3.15 small calories per square centimeter per minute, or 0.0526 radim. But the aqueous absorption in the infra-red region must first be examined more critically.

The latest advances in the study of the invisible spectrum enable us to apply some rough tests. Scheiner, in his recent work, Strahlung und Temperatur der Sonne (p. 51), adopts 7,760 centigrade degrees on the absolute scale as a probable value of the solar photospheric temperature assuming unit emissive power, and 13,800° for an emission coefficient of $\frac{1}{10}$, although it is also shown that if the sun radiates according to Stefan's law for a black body, its effective temperature can not be much over 6,000°. Adopting Wien's law of radiation as modified by Paschen,

$$\log (I \times \lambda^5) = \log c_1 - c_2 \log e \times \frac{1}{\lambda T}$$

(where $c_1 = 633{,}000$, and $c_2 = 5 \times \lambda_{\text{max.}} \times T = 5 \times 2{,}891$, are constants, T is the absolute temperature, and I is the intensity of radiation of wave-length λ), if the sun radiates like an absolutely black body, and if a maximum occurs in the spectrum at $\lambda = 0.45\ \mu$ for the unabsorbed normal energy-curve of the spectrum from photospheric radiation, then this corresponds to a solar temperature of $T = 6{,}424°$. The energy-curve computed by the law just given, after reduction for the absorption by the solar and terrestrial atmospheres, agrees with observation between $\lambda = 0.3$ and $\lambda = 1.0\ \mu$, but departs more and more widely beyond the latter point, until at $9.0\ \mu$ the computed ordinates are only $\frac{1}{35}$ of the observed values at points of least absorption. Hence, it is certain, as Scheiner has noted, although without applying any numerical test, that the sun does not radiate like an absolutely black body. Moreover, it does not radiate at any single temperature, but the photosphere being composed, as Langley has shown (Am. Jour. Sci. (3), vol. 7, p. 87, 1874), of brilliant granules, having a high emissive power, and occupying only one-fifth of the surface, while the background formed by the remaining four-fifths is relatively dull, it follows that the total photospheric radiation is made up of the radiant emission from particles at very different depths, and having doubtless a wide range of actual and effective temperature. Hence, the unabsorbed spectral energy-curve must be the integration of many curves corresponding to many temperatures, and presumably none of them agreeing with that of the ideal black body. The result is to raise the ordinates (intensities) corresponding to the longer waves.

The theory, however, may still be used to supply an estimate of the solar curve before absorption by the earth's atmosphere, and hence of the solar constant, if we distribute its errors by a logarithmic curve which gives a spectral energy-curve similar to that enveloping the maxima of the observed solar prismatic curve. The observed intensity in the rock-salt prismatic spectrum at $1\ \mu$ is one hundred times as great as at $9\ \mu$ (37° 12′ minimum deviation)[4], and the transmissions for points of least absorption are about 0.82 and 0.88, respectively; but the intensities by Paschen's formula, reduced to the prismatic curve, are 58,006 and 16.4, or in the ratio of 3,537 to 1; and as probably no one would maintain that the absorption of the solar atmosphere is capable of producing such diversity, it seems proper to attribute the divergence from the energy-curve of a black body to some peculiarity in the emissive power of the solar substance. In the following table it is to be noted that the end values are given by experiment, and the intermediate ones are obtained by taking equal logarithmic corrections to the theoretical curve for equal differences of wave-length. A small correction is made at $1\ \mu$ to allow for band absorption. The remainder of the loss here may reasonably be assigned to selective scattering.

Wave length (μ)	1	2	3	4	9
Intensity (black body)	3537	2018	357	86.2	1
Logarithmic factor	.0240	.0372	.0575	.0891	.8000
Intensity (computed)	84.9	74.9	20.5	7.7	0.8
Envelope at maxima of solar curve	70	60	12	5	0.7

The values in the last line are for a curve tangent to the observed maxima and having a maximum ordinate of 100 between Ψ and Ω. Inserting the sinuosities from the bolographs obtained by Langley and Abbot, and completing the curve by the measures of solar radiation for long waves, the areas, measured by the planimeter, are:

	λ	Outside.	After absorption.
	1.2 — 2.0 μ	67.7	37.2
	2.0 — 5.0	25.8	12.4
	5.0 — 15.0	6.5	0.6
Total:	1.2 — 15.0 μ	100.0	50.2

The absorption in the infra-red varies so slowly with the increase of air mass, being produced almost wholly by the

[4] See "The solar and the lunar spectrum." By S. P. Langley, assisted by F. W. Very. Memoirs National Academy of Science, vol. 4, Second Memoir, Fig. 2a.

upper air, that we may apply the value thus obtained from spectral measures at sea level to the Lone Pine observations, getting for the part of the spectrum beyond 1.2 μ[5] a transmission of 50.2 per cent, which agrees so nearly with that already deduced for the radiant energy of shorter wave-length than 1.2 μ, namely, 48.6 per cent, that the assumption of equal *average* absorption in the two regions seems justified. As thus reduced, the Mount Whitney observations yield the following values for the solar constant (reduced to sun's mean distance):

		Calories per sq. cm. per minute.
From Mountain Camp observation		3.072
From Lone Pine observations	3.233 3.130	3.182
Mean		3.127

The agreement between values deduced from noon measures at high and low stations is satisfactory, and that for measures at high and low sun is equally good, or becomes so with only trifling modifications of the adopted constants. The separation of the coefficients for scattering of the rays by fine particles into air and dust factors is therefore justified.

It is commonly supposed that the larger portion of the heat produced by the absorption of the solar rays remains in the lower layers of the atmosphere, because these are richest in the vapor of water and in dust. See, for example, M. Crova's Mesure de l'intensité calorifique des radiations solaires et de leur absorption par l'atmosphère terrestre, p. 1, Paris, 1876. M. Radau, Actinometrie, p. 12, says: "In proportion as the rays penetrate into the atmosphere, they encounter layers more and more dense, and the loss which they experience through unit path is proportional: (1) to the actual intensity of the beam; (2) to the density of the layer which they traverse; (3) to a constant coefficient of absorption ... which varies with the nature of the rays." On page 14 (loc. cit.) it is said that "the absorption is due in great part to the vapor of water distributed in the lower layers of the atmosphere," although it is recognized (page 18) from the observations of Desains, that the ratio of long-waved solar radiations on a high mountain to those at sea level must diminish when the air is very moist. Nevertheless, no objection is made to the use of formulæ in which the aqueous component of the absorption is assumed to be proportional to the density of the aqueous vapor.

The actual case is much more complicated. Selective reflection increases in the lower atmospheric layers, but does not warm them. Low layers of a moist atmosphere become hot because they absorb the rays of extremely long wave-length emitted by the heated soil. The sun heats these layers indirectly by first heating the ground, but contributes little heat directly, since the rays absorbable by aqueous vapor have been nearly all sifted out of the sunbeam before this reaches the lower atmospheric layers. On the other hand, the higher atmosphere, which contains a smaller quantity of aqueous vapor, is the first to attack the incoming rays. It is in the upper layers that the aqueous absorption of the solar infra-red rays takes place chiefly, and these are therefore the layers which are most warmed by the direct rays of the sun. I have noted elsewhere (Atmospheric Radiation, p. 123) that after rising above the comparatively thin layer of convectionally heated air, that portion of the diurnal range of temperature due to the immediate absorption of the solar rays may be expected to increase up to nearly the limit of the aqueous atmosphere, and it is surmised that this variation may possibly approach a ten-fold ratio of that which occurs at altitudes of one or two kilometers.

Professor Bigelow (Report on the International Cloud Observations, United States Weather Bureau, 1898-99, p. 786,) finds that "the number of calories per kilogram required to transform the adiabatic state into the actual state of the atmosphere," as inferred from cloud phenomena, and to some extent confirmed by the results of balloon ascensions, varies from 1 or 2 calories, at the height of 1,000 meters, to 10 or 11 calories, at an altitude of 13,000 meters. This phenomenon, it seems to me, is attributable to the direct solar influence upon the higher layers of the air. The annual range of temperature of the upper air has also been found to be unexpectedly large, a fact which must follow from the present argument, but which has not been heretofore anticipated, because of the erroneous conception that the sun's rays are but little absorbed by the upper air.

Atmospheric absorption of solar rays, using the term in the wide sense to cover every kind of depletion of the incoming rays, must be treated under two heads: (1) Band absorption, which takes place mainly in the upper air and at longer wave-lengths, which is quite local in its action, and must be expressed in terms of incipiency, rather than as a function of the density of the active absorbent; and (2) selective reflection, which acts chiefly in the lower atmosphere and at short wave-lengths, although it is not without some effect throughout the spectrum. The action in this case varies with the density of the absorbent medium, whether this be dust or air. A barometric formula expresses the air variation, but dust varies with the direction and strength of the wind, the height above sea level, the relative humidity, etc.[6] The usual formulæ for atmospheric absorption has been devised on lines suggested by the laws of luminous extinction through turbid media. They make no attempt to deal with the more troublesome line and band absorption, and the latter, at present, can best be treated graphically.

I can not insist too strongly on the necessity of the spectrobolometric method for obtaining a correct value of the solar constant; but when thus found, the knowledge may be used in interpreting the results of actinometric series, which, taken alone, lead to no definite result.

From Angström's work, Intensité de la radiation solaire à différentes altitudes, recherches faites à Ténériffe, 1895 et 1896, Upsala, 1900, I take the following summary of measurements of solar radiation, made with the compensating pyrheliometer of his invention:

Sun's zenith distance	The Peak: Barometer 492 mm., altitude 3,683 m.		Alta Vista: Barometer 518 mm., altitude 3,252 m.		Cañada: Barometer 597 mm., altitude 2,125 m.		Guimar: Barometer 734 mm., altitude 360 m.	
	ϵ	I	ϵ	I	ϵ	I	ϵ	I
°	*Atm.*	*Cal.*	*Atm.*	*Cal.*	*Atm.*	*Cal.*	*Atm.*	*Cal.*
85	6.61	0.925	6.96	0.916	....	....	....	....
80	3.60	1.184	3.79	1.156	4.38	1.055	5.38	0.786
75	2.46	1.299	2.59	1.287	2.99	1.208	3.68	0.957
70	1.88	1.388	1.98	1.370	2.28	1.288	2.80	1.049
60	1.291	1.490	1.359	1.468	1.568	1.402	1.927	1.189
50	1.006	1.553	1.059	1.527	1.222	1.472	1.502	1.269
40	0.845	1.585	0.889	1.565	1.027	1.508	1.262	1.314
30	0.748	1.606	0.787	1.583	0.909	1.529	1.117	1.357
20	0.689	1.619	0.725	1.595	0.837	(1.530)	1.029	1.375
10	0.657	1.624	0.692	1.610	0.799	(1.540)	0.981	1.391
5	0.650	1.627	0.684	1.613	0.790	(1.542)	0.971	1.401

The curves showing the variation of intensity with air mass, intersect the axis of intensities near 2.0. If the solar constant be 3.1 calories, as has been strongly indicated by Langley's measures on Mount Whitney, as well as by those of Crova and Hanski in the Alps, its value at the time of these observations, near the summer solstice, must have been 0.1 smaller, or 3 small calories per square centimeter per minute. Of this, about one-third has disappeared, that is to say, about 1 calory is not accounted for by the increase of the

[5] Langley's bolometer makes the energy in this region about one-third of that in the whole spectrum, but as the instrument does not absorb the long waves completely, the ratio is certainly greater.

[6] We must guard against the supposition that the dust itself is necessarily dry. It may be only an exquisitely fine, watery mist.

air mass. Let us assume that this represents the loss by band absorption, and, as a first approximation, that this loss is the same for both stations. The difference of 0.15 to 0.25 calories between the highest and lowest stations for the same values of ε, must be largely due to dust, and since this concerns an initial radiation of 2 calories, a difference of 10 per cent must be made in the dust allowance at upper and lower stations.

Let A = the solar constant, B = band absorption, R = coefficient of transmission for scattering by air molecules, D = coefficient of transmission for scattering by dust (D_1 for mountain, D_2 for valley), I = intensity of observed radiation.

$$I = (A - B) \times R^{\varepsilon} \times D^{\varepsilon'}.$$

Assume $R = 0.95$, $D_1 = 0.85$, $D_2 = 0.75$, $A - B = 2$.

(1) For $\zeta = 5°$, mountain $\varepsilon = 0.65$, $\varepsilon' = 1.00$, $I = 1.627$;
(2) valley $\varepsilon = 0.97$, $\varepsilon' = 1.00$, $I = 1.401$.
(3) For $\zeta = 80°$, mountain $\varepsilon = 3.60$, $\varepsilon' = 1.92$, $I = 1.184$;
(4) valley $\varepsilon = 5.38$, $\varepsilon' = 2.56$, $I = 0.786$.

	I (computed).	Error.
(1)	$2 \times .95^{.65} \times .85 = 1.624.$	$-0.003.$
(2)	$2 \times .95^{.97} \times .75 = 1.427.$	$+0.026.$
(3)	$2 \times .95^{3.60} \times .85^{1.92} = 1.216.$	$+0.032.$
(4)	$2 \times .95^{5.38} \times .75^{2.56} = 0.727.$	$-0.059.$

The values of ε' have been computed on the same basis as in the example already given for Mount Whitney. That for the valley (2.56) is evidently too large, that is to say, there is not as much difference between the low-sun dust conditions at the top and bottom of the mountain as has been assumed in this computation, or as seems to have existed at Mount Whitney, where also the double ratio for k', combined with the 5 : 3 ratio for r in the computation of ε', was found to be a trifle too large. It is, of course, perfectly feasible to choose values which shall make the differences disappear, but I prefer to let the example stand as it is, for the instruction which it gives, my present purpose being to illustrate methods, and not to rectify results.

The quantity $A - B$ can not be a constant, but must vary with the moisture in the upper air, and, in general, must change with the seasons and the altitude. Thus, for the observations on Mount Whitney, which were made at a high altitude, and in a very dry atmosphere, $A - B$ is approximately 2.5. In the Tropics $A - B$ is probably nearer 1.5.

Let C = absorption of total solar radiation by carbon dioxid, assumed equal to 2 per cent and constant. W = absorption of total solar radiation by aqueous vapor, which is found to be dependent both on the absolute and the relative humidity, the absorbent power of a given quantity of moisture increasing as its state approaches that of saturation. Then

$$(a) \qquad W = -\frac{0.999 + \ldots}{1 + log\,(1 + fh)^y},$$

$$(b) \qquad B = A.\,(1 - C).\,W,$$

where, if f, the tension of aqueous vapor, is given in millimeters, and h is the fraction expressing relative humidity, the exponent y has the value 1.65.

Four cases may be taken, illustrating a wide range of terrestrial conditions from highest mountain, or coldest arctic climate, to the extreme moisture and heat of the Tropics.

(1)	$f = 1$	$h = \frac{1}{10}$	$fh = 0.1$
(2)	$f = 2$	$h = \frac{1}{4}$	$fh = 0.5$
(3)	$f = 20$	$h = \frac{1}{2}$	$fh = 10.0$
(4)	$\left\{ \begin{array}{l} f = 25 \\ f = 33.3 \\ f = 50 \end{array} \right.$	$\left. \begin{array}{l} h = 1 \\ h = \frac{3}{4} \\ h = \frac{1}{2} \end{array} \right\}$	$fh = 25.0$

It is by no means certain that f and h enter as their product in the complex function with the variety of conditions under (4), ranging from those of a rainy season in the torrid zone, to that of a tropical desert, but I shall here assume this. The formulæ (a and b) give:

(1)	$W = 0.1159$	$B = 0.341$	$A - B = 2.659$
(2)	0.1680	0.494	2.506
(3)	0.4287	1.260	1.740
(4)	0.4984	1.465	1.535

The conditions on Mount Whitney fall between those of (1) and (2); those on Teneriffe between (2) and (3); while (3) appears to suit the average summer conditions at sea level in the temperate zone. It is this quantity ($A - B$), and not the solar constant (A), which is given by most of the published reductions of actinometric measurements.

If ever the law according to which the quantity ($A - B$) varies with the moisture can be established with greater precision, then the long series of actinometric measures from which at present nothing more than an estimate of this quantity can be deduced, will not have been made in vain.

The series of eighteen years duration, which is summarized by M. Eon in the Bulletin météorologique du département de l'Herault, 1900, p. 133, demonstrates the increase of the quantity ($A - B$) in winter and spring, verifying a fact, originally made known by M. Crova. The transmission by atmospheric aqueous vapor is greatest in the spring months. Langley and Abbot (Annals of the Astrophysical Observatory, etc., vol. 1, p. 207) find that at this season the aqueous bands in the spectrum become narrower and not quite so deep.

Crova's actinographs have demonstrated a diurnal variation of radiation connected with the convective distribution of moisture in the upper air, which depends upon the aqueous vapor supplied by surface evaporation. It is reasonable to expect that a more complete theory of the absorptive process will enable us to utilize observations made at all hours, deducing consistent values of the solar constant, whether the observations be made at morning, noon, or afternoon.

Greater attention should be paid to the theory of actinometers, and to the determination of their corrections, reducing all values to the absolute standard Langley's critique of Violle's actinometer (Researches on Solar Heat, chapters 5, 6, and 8), and Chwolson's investigation of the theory of Angström's differential pyrheliometer in Wild's Repertorium für Meteorologie (vol. 16, No. 5, 1893), as well as his critique of 166 pages on various actinometers (Wild's Repertorium für Meteorologie, vol. 15, No. 1, 1892), should be studied by all who wish to enter upon similar investigations.

Crova's absolute actinometer of 1898 (Comptes Rendus, vol. 126, p. 394), in which the receiving body is a disk of copper, 4 centimeters in diameter and 0.5 centimeter thick, blackened in front and polished on the other side, suspended by three fine threads in a water jacket, and having its excess of temperature above the blackened walls directly measured by an iron-constantan thermopile, appears to be a valuable instrument. It, as well as Violle's actinometer, however, should be used to measure initial rates of heating with both positive and negative values of θ.

Angström's differential pyrheliometer, as modified by Chwolson, employs a pair of receiving bodies very similar to Crova's disks, but without the advantage of the protecting water jacket, an advantage, however, which has not been fully utilized by Crova. Professor Callendar has shown (British Association for the Advancement of Science, Report for 1899, p. 36) that there is an appreciable time-lag in the heating of metallic disks considerably thinner than those of either Crova's or Angström's instruments. If used with equal positive and negative excesses in relation to the standard temperature of an enclosure, there is compensation, and the slowness of the conductive process is of less avail to vitiate the result.

Even where metal strips as thin as 1 or 2 microns are employed as a receiver, as in Angström's electric compensation pyrheliometer, we can not be sure that the heat is fully recorded. I have found (Atmospheric Radiation, pp. 13–16) that such thin strips lose their heat mainly by convection, and that two minutes may elapse before complete convective and conductive equilibrium is established. In some of these instruments, the rear surface is left bright with the intention of confining the loss of heat chiefly to the front surface; and this would be thereby accomplished satisfactorily did not convection form so essential a part of the total loss. This, of course, goes on as well at the bright surface as at the dark. The heat produced by absorption of solar radiation at the blackened surface, escapes more easily than it enters, because the thin layer of black absorbent material transmits the long outgoing ether-waves much more freely than it does the shorter waves coming from the sun. Thus, it appears probable that the indications given by all of these so-called "absolute" actinometers are a little too small, and that we should not depend too much upon the agreement of measurements by different instruments and methods, since these may have equal constant errors. The only remedy for these defects lies in a most searching investigation of the complete theory of these instruments.

ICE CAVES AND FROZEN WELLS AS METEOROLOGICAL PHENOMENA.

By H. H. KIMBALL, Weather Bureau.

INTRODUCTION.

On page 71 of the MONTHLY WEATHER REVIEW for February, 1901, the Editor has stated that numerous natural ice caves are on record analogous to the interesting example near Flagstaff, Ariz. At his suggestion a special study of the literature bearing on the subject was undertaken by me, and I am now quite ready to agree with Mr. J. Ritchie, Jr.,[1] who says that "The best informed of scientists, even, are not aware of the mass of matter that has been written and published on this subject, owing to its distribution through the proceedings of so many learned societies." It was not until much time had been spent in searching through these proceedings, as well as through other departments of literature, that I became aware of a book entitled Glacières or Freezing Caverns, published in 1900, by Edwin Swift Balch, a member of the Philadelphia bar, and ex-president of the Geographical Club of that city, in which he mentions over one hundred and fifty authors whose writings were consulted by him in the preparation of his book. He also gives a list of some sixty-five places where subterranean ice forms in the United States, and nearly three hundred places for the whole world.

European ice caves.—So thoroughly has Mr. Balch covered this ground that it seems hardly necessary for me to review it. Mention will be made, however, of a work entitled Ice Caves of France and Switzerland, by Rev. G. F. Browne (London, 1865), and also of an article in Once a Week, Vol. II, p. 639, by Mr. Harold King, in which he gives an account of a visit to the famous Schafloch, an ice cave in Switzerland. From the descriptions of these two writers, in conjunction with those of Mr. Balch, it is evident that many of the ice caves of Europe are very grand affairs. Not only are the bottoms and sides ice coated, the latter often to unknown depths, but stalactites and stalagmites of great size and beauty are frequently to be found, giving the caves most fantastic appearances.

But the ice caves of the United States, if not so grand as those of Europe, are equally as interesting from a meteorological point of view. We therefore quote from several writers, in order that it may be seen under what a variety of conditions subterranean ice deposits are to be found.

[1] Paradoxical Phenomena in Ice Caves, Science Observer, April, 1879.

Ice cave in Washington.—In the Overland Monthly for 1869, Vol. III, p. 425, Mr. R. W. Raymond has given an account of a visit to a cave in Washington, in the Cascade Mountains, from which at that time ice was "packed" on the backs of mules and horses. He describes the cave as a channel in the basalt through which the melted lava continued to flow after the surface had become cooled and formed a crust. When, from any cause, the source of the melted lava has been cut off, these channels have been left empty, and it is in them that the ice is found.

Decorah, Iowa, ice cave.—In the Scientific American for March 29, 1879 (Vol. XL., p. 196), there is a description of a cave near Decorah, Iowa, by an anonymous writer, who thought that the ice formed in it only in summer and melted away every winter. But in the Scientific American Supplement for November 26, 1898, Mr. Alois F. Kovarik published the results of systematic observations of the temperature and the formation of ice in this cave, showing conclusively that the temperature fell steadily during the winter, that ice formed during the spring, and disappeared during the latter part of the summer.

These two caves, with the one near Flagstaff, Ariz., already mentioned, appear to be among the best examples of natural ice caves that are to be found in the United States, although there is a deposit of ice in the abandoned Cheever Mine at Port Henry, N. Y., that is fully as extensive. In all these cases the ice is deposited at a point in the cave considerably below the level of the entrance.

Ice beds in Connecticut.—In years past there have appeared descriptions of ice deposits that were to be found in deep ravines and gorges in the towns of Meriden[2], Northford,[2] and Salisbury,[3] Conn. In caverns or among the loosely piled boulders at the foot of the nearly precipitous sides of the ravines and under the shade of forest trees ice was said to form in winter in large quantities, and the rocks and trees protected it from the heat of summer so effectually that it was sometimes preserved until the early autumn. Of late years the existence of these ice deposits appears to have been nearly forgotten. In fact, recent letters to voluntary observers and others in or near these towns have generally elicited the statement that the ice formed only in a small way and was not preserved much longer than at other points in the forests among the mountains of that region. But our very energetic observer, Mr. L. M. Tarr, of New Haven, Conn., personally visited the ravine at Northford on June 19, 1901, with a party of friends, and reports as follows:

"Not far from the ravine the side of the mountain, which is composed of broken trap rock, is very steep. There are many trees on the top of the mountain and a few at its base, but during the most of the day this mass of rock is exposed to the direct rays of the sun. In these rocks, about 4 feet below the surface, much to my surprise we found ice. It was bedded in between the rocks, and could be taken out only in small pieces. There was considerable dirt mixed with it, as stated by Professor Silliman in 1822. I had my camera with me and took a snap shot of the place. (See Plate I, fig. 1.)

"The trees in the background of the print are on the edge of the ravine, which we examined throughout its entire length. At its bottom, near the base of the mountain, it is filled with small boulders, and under these are heaps of dead leaves and rubbish. I dug under some of the heaps of leaves, but found no ice. In ascending the ravine, we found two or three places where very cold water was trickling out of the rocks. I thought its temperature was not far from the freezing point, and concluded that it came, not from a spring, but from melting ice among the rocks. These were too heavy to move without a

[2] Silliman's American Journal of Science and Arts, 1822, vol. 4, pp. 174–177.

[3] Silliman's American Journal of Science and Arts, 1824, vol. 8, p. 254.